Coil Pulsers for Radar

By E. PETERSON

RADAR systems in current use radiate short bursts of energy developed by pulsing a high-frequency generator, usually a magnetron. One means of developing the requisite impulses employs a non-linear coil and is termed a coil pulser. Such pulsers are found in substantial numbers among the Navy's complement of precision radars. Most fire control radars on surface vessels are equipped with them, and all modern radar installations on submarines are so equipped for search and for torpedo control.

History of Development

Coil pulsers had their origin in the magnetic harmonic generators first built for the telephone plant. Multi-channel carrier telephone systems in general use throughout the Bell System require numbers of carriers, harmonically related in frequency. These are derived from non-linear coil circuits[1] which convert energy supplied by a sine wave input into regularly spaced, sharply peaked pulses.

When development was started on precision radars, one of these circuits generating a power peak of a few hundred watts, several microseconds in duration, was adapted to the purpose.[2] Its output was shaped and amplified by vacuum tubes of sufficient power to key or modulate the ultra-high-frequency generator of the radar transmitter. All early fire-control radars were made up in this way; hundreds are still in use.

The next development of pulsers for fire-control radars was directed toward higher-powered pulses, shorter in duration for good range resolution. These had to be provided by a small package pulser, small enough and rugged enough to mount integrally with the magnetron and the antenna. The power rectifier was to be located at any convenient distance, and the rectified voltage had to be low enough to permit the use of standard low-voltage cables. These requirements put high vacuum tubes at a disadvantage in handling the finally developed pulses. Pulse transformers had not attained their present state of perfection in dealing with short pulses at this early stage and the pulser therefore had to work the magnetron directly.

[1] Magnetic Generation of a Group of Harmonics, by Peterson, Manley and Wrathall, *B.S.T.J.*, vol. XVI, p. 437, 1937.

[2] Fire-Control Radars, by Tinus and Higgins, *B.S.T.J.*, January, 1946.

One arrangement developed by W. Shockley to meet these requirements used a thyratron as a switch to generate pulses. High vacuum tubes were used at low voltages for comparatively long-time intervals in the driving circuit. Deficiencies of the thyratrons available at that time prevented the generation of pulse powers as high as required. With the earlier experience on low-level coil pulsers in mind, it was natural to think of using a non-linear coil for switching pulses at high level, in place of the thyratron. Much development was required to arrive at suitable circuits embodying the basic ideas, to build non-linear coils capable of withstanding high voltages, to proportion the circuit elements for efficient operation at specified powers and pulse durations, and to shape the output pulse to the desired flat-topped form.

This development resulted in a power pulser mounted in an oil-filled steel box, with associated high vacuum tubes of the sturdiest sort mounted externally, operated from a 1200 volt d-c. supply. It was suitable for installation integral with the antenna, and rugged enough to withstand gun blast and shock. Life of the pulser box components is long, and performance stable with time and temperature. The time of pulse emission is linked precisely to the input wave, practically independent of voltage and frequency variations over a suitable range. Such precision timing, or freedom from jitter, permits starting the indicator equipment in advance of the pulse emission time so that target ranges may be accurately measured. The power rectifier voltage is much lower than that of the pulse applied to the magnetron, and the pulser works directly into the magnetron without requiring an intermediary pulse transformer.

Subsequent developments left unchanged the general form of the circuit and its mounting, but were devoted to achieving various pulse widths, powers, and pulsing rates to suit different applications. Pulse widths covered a range from two-tenths to over one microsecond, peak powers ranged from 100 to 1000 kw, and pulsing rates ranged from 400 to 3600 pulses per second.

Non-Linear Coil Structures

An idea of the general form and makeup of non-linear coils used in various radar developments can be had from the photograph of Fig. 1. All cores shown there are made of molybdenum permalloy tape, one mil thick. Insulation is electroplated on the tape in a silicic acid bath, and the tape is wound in ring form. After the standard magnetic anneal of 1000°C in hydrogen, the coating of insulation a fraction of a mil thick adheres firmly to the tape.

The smallest coil shown in Fig. 1 seen just in front of the oil filled container in which it is mounted is used for low-power pulse generation. Its core weighing 7 grams is wound on an isolantite form.

The two larger coils shown are used in power pulsers. Their cores are made up of self-supporting rings. The smaller coil has a core weight of one kilogram and is used at voltages up to 25 kv. for the generation of power peaks of the order of 100–250 kw. Phenol fibre is used to support and position the core and winding. The larger core has a weight of 13 kg. and is used at a voltage of 40 kv. in a pulser generating power peaks of one megawatt. Glass-bonded mica and built-up mica are used for support and

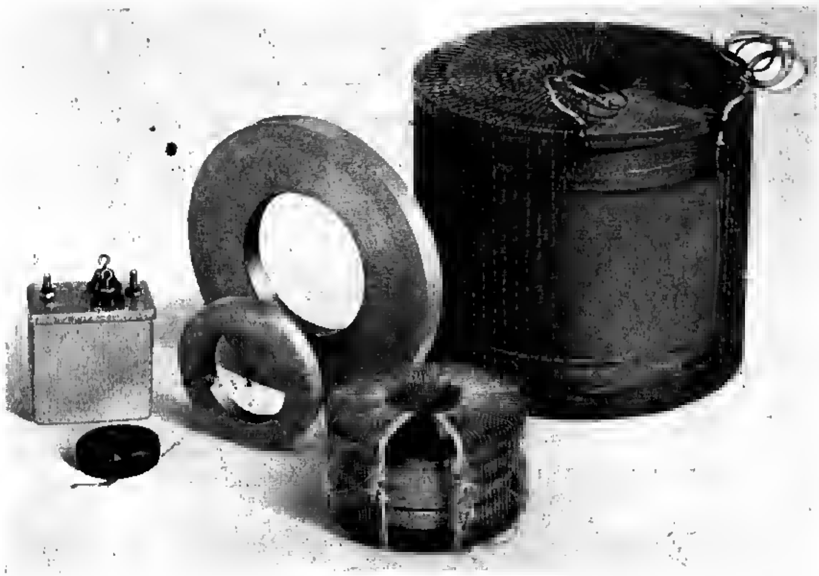

Fig. 1—Non-linear coils used in various radar transmitters. The smallest coil at the left, seen in front of its container, is used for low power pulse generation. The two larger coils are used in power pulsers developing 200 KW and 1000 KW peaks, respectively. The core rings of molybdenum permalloy tape are assembled into the coils shown.

positioning of the core rings and windings. The coils are assembled with other passive elements of the pulser network and the whole immersed in oil.

Operating principles of the two types of pulser circuits in which these coils are used are now to be discussed.

Low-Level Pulser

A schematic of the circuit used for developing low-power pulses is shown in Fig. 2a. Sinusoidal driving current (i_1) is introduced from the left, and a sharply peaked wave (i_2) is developed in the right-hand mesh. A resonant circuit (L_1C_1) serves to prevent dissipation of the generated pulse in the input mesh, and to tune out the input reactance at the driving frequency.

Capacitance and resistance elements (C_2R_2) in conjunction with the non-linear coil (L_2) make up the output mesh.

A complete cycle of the input wave is depicted in Fig. 2c, placed to correspond with the *B-H* loop of the non-linear core shown above it in Fig. 2b.

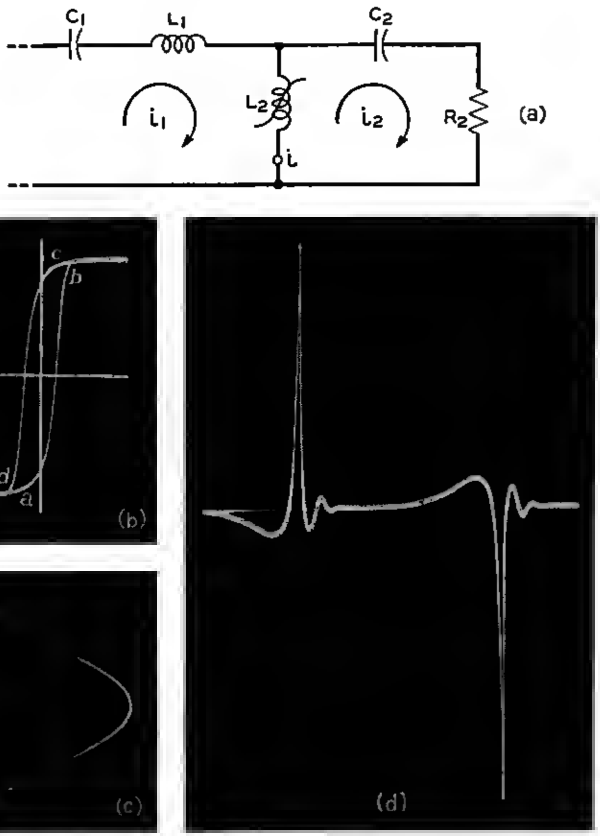

Fig. 2—Low-level coil pulser.

(a) Circuit diagram showing input tuning C_1L_1, non-linear coil L_2, output condenser C_2, and load resistor R_2.

(b) *B-H* loop of non-linear coil, with letters marking transitions between permeable and saturable regions.

(c) Sinusoidal input current wave scaled and placed to correspond with the horizontal scale of Fig. 2b.

(d) Pulsed output wave, i_2 as ordinate; i_1 as abscissa.

Action of the circuit is now to be followed throughout a cycle, starting with the input wave at its maximum negative excursion, condenser C_2 uncharged, and the core in its lower saturation region. Here the slope of the *B-H* loop and the corresponding differential permeability and inductance are

small. Hence the voltage drop across the coil is small. Little current flows in the output mesh, and practically all the input current flows through the coil. Matters are much different during the next interval in which the increase of current in L_2 brings the core into the permeable region *a-b*. Here the differential permeability is large so that part of the input current is diverted to the output mesh, charging the output condenser until upper saturation is reached at *b*. There the coil inductance falls to a low value, switching most of the condenser voltage across the load resistance. A current pulse accordingly develops in the output mesh lasting until the condenser charge is exhausted. The form of the current pulse shown in Fig. 2d approaches that of a highly damped sinusoid, and the pulse duration and magnitude are functions of the three elements of the discharge mesh. During the next half-period of the input wave, the same situation develops as in the first half-period, except that the corresponding currents and voltages throughout are reversed in sign.

According to this description the non-linear coil acts like a switch which automatically shifts the inductance from relatively high to relatively low values at specific coil currents. When the core is driven well into saturation, as is the case here, the ratio of these two inductances can be made large, usually in the neighborhood of several thousand. One feature of its action important from the efficiency standpoint is that the pulse occurs for the most part in the saturation region, where the contribution to eddy loss is small. The principal core loss occurs in the permeable region while the output condenser is charging, when variation of current through the coil occurs at a relatively slow rate.

In low-level radar applications the pulser output feeds a vacuum tube amplifier biased so that pulses of just one polarity are passed, the other oppositely poled pulse being cut off.

Since the range sweep of the radar receiver is initiated prior to pulse emission, the pulse should occur at a time linked precisely to the input wave. Otherwise the received pulse would be blurred introducing an uncertainty in measuring target range. No blurring (jitter) is visible with normal coil pulser operation. To get a measure of any variations which might be associated with core magnetization, tests were performed on a communication circuit in which jitter occurring at an audio rate would show up as noise. Measurements with a sensitive noise meter indicate the corresponding variation of pulse emission time to be smaller than 10^{-9} second.

Power Pulser

Operating Principles

The power pulser has the same type of discharge circuit as the low-level pulser just discussed. It differs in using a d-c. rather than an a-c. power

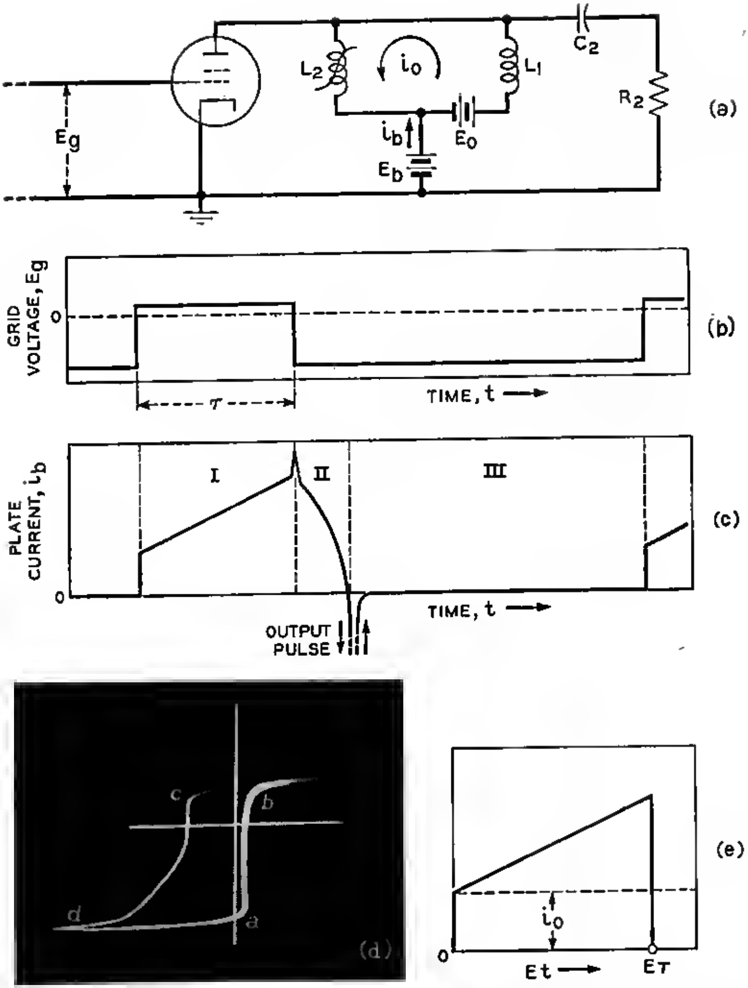

Fig. 3—Power pulser.

(a) Simplified circuit diagram showing charging tube at left, bias supply E_0, plate power supply E_b, linear coil L_1, non-linear coil L_2, output condenser C_2, and load resistor R_2.

(b) Rectangular wave of grid voltage impressed upon the tetrode of Fig. 3a. The tube conducts during the time τ in each cycle, and is cut off outside that interval.

(c) Plate current wave (i_b) corresponding to time scale of (b). During interval I, current is drawn through the paralleled inductors and the charging tube. At the end of this interval the tube is cut off and remains so until the start of the next cycle. During II, the magnetically stored energy is transferred to the condenser through R_2. At the same time the non-linear coil is brought toward saturation. During III saturation is reached; energy stored in C_2 is transferred to the load resistor through L_2 in a short pulse.

(d) *B-H* loop of non-linear coil used in the circuit of (a). Letters mark the most important transitions. During interval I magnetization proceeds from the lower left through *a* up to *b*; during II magnetization decreases past *c* down to *d*, and during III it extends far beyond the limits of the Figure to the left, returning to the neighborhood of *d* upon completion of the output pulse.

(e) Plot of current in linear coil during charging interval I against the product of coil voltage and time. Enclosed area represents energy stored in the linear coil. The rectangular area under the dashed line drawn through i_0 represents that part of the stored energy which varies with bias current.

source, and in charging the load condenser by a free, rather than by a forced oscillation. Energy for the free oscillation is taken from the d-c. source in a preliminary operation, in which energy is stored in a linear inductor. This preliminary operation consists in closing a d-c. path from the plate power supply through the linear inductor by means of a high vacuum tube, permitting current to build up with time. After a predetermined time has elapsed, the tube circuit is opened, the d-c. path is thereby interrupted, and energy stored in the inductor transfers to the load condenser. In this way the voltage to which the load condenser is charged can be made many times greater than the voltage of the plate power supply. The simplified circuit of Fig. 3(a) will serve to bring out salient operating features. Conduction of the tetrode at the left is controlled by a rectangular wave of grid voltage (Fig. 3b) developed by a multivibrator (not shown) which swings the grid from a potential below cutoff to one just above cathode potential. The plate power source E_b feeds two inductors in parallel, L_1 being linear, and L_2 non-linear. A small biasing voltage E_0 drives polarizing current i_0 through the two inductors in series.

The preliminary operation which serves to transfer energy from the main power source to the inductors is initiated when the tetrode grid is driven positive. Current from the main source builds up through the paralleled inductors and the tetrode as indicated on Fig. 3c, interval *I*. The region in which the non-linear coil works may be seen from the hysteresis loop of Fig. 3d. Its operating point is displaced to the left of the origin near *d* by the bias current. When the tetrode conducts, current in the non-linear coil rises rapidly at first in the lower saturation region until *a* is reached. The rise thereafter is comparatively small and slow in traversing the permeable region *a*-*b*, while at the same time current builds up in the linear coil at a much greater and practically uniform rate. When the core of L_2 reaches saturation near *b* its inductance again drops, preventing further rise of current in L_1. At this time the tetrode is driven below cutoff and remains out of the picture until the start of the next cycle.

The second interval, in which energy is transferred from the linear inductor to the load condenser, starts with the cutoff of tetrode current. This transfer is effected in an oscillation with frequency determined mainly by the paralleled inductors and the load condenser. In this interval II of Fig. 3c, current through the non-linear coil falls suddenly at first from *b* to *c* and then more slowly from *c* to *d*. The rate of change in region *c*-*d* is much greater than that in *a*-*b* as indicated by the fainter trace in Fig. 3d, so that eddy currents in the core are increased and the slope of the descending branch of the loop reduced correspondingly. Thus some of the energy previously stored in the linear inductor is used up in completing the magnetization cycle and this part, consequently, is not available for transfer to the load

condenser. The maximum voltage to which C_2 is charged in this interval is made much greater than that of the d-c. power source (E_b). The ratio of these two voltages depends upon the ratio of the inductance charging time in the preceding interval to the oscillation period. Both factors can be varied over wide limits, and step-up ratios of roughly ten to twenty are generally used.

The third interval starts with magnetization of the non-linear core near point d on the loop, where the inductance again drops. This situation is precisely the same as that previously described for the low-power pulser. As a result the condenser discharges through the load resistance at the time indicated in Fig. 3c, driving the core far into saturation with a field of the order of a hundred oersteds. This field extends too far to the left of point d to be shown in Fig. 3(d). Here the differential permeability approaches unity, and the correspondingly low inductance permits a rapid build-up of pulse current. Evidently but one pulse is produced each time the tetrode conducts, and the number of pulses produced per second is changed simply by varying the input frequency without requiring any circuit change, power dissipations permitting.

Energy storage in the linear coil depends upon its inductance, upon the bias current, and upon the peak current reached during the tetrode conduction interval. A plot of the current in L_1 against the product of time and of voltage across the coil permits this energy to be represented as an area (Fig. 3e). Evidently a given area can be made up by varying the relative sizes of its component triangle and rectangle, only the latter varying with bias current. If for example the bias is reduced to zero, the rectangle would vanish and the peak current would have to be increased to attain the original amount of stored energy. The higher maximum current requires more cathode emission of the tetrode and leads to greater plate power dissipation. Thus in addition to determining the energy stored, the amount of bias is one of the factors determining power dissipation capacity and emission which must be provided in the driving tube or tubes. Additional factors enter to make a bias corresponding to d (Fig. 3d) the most favorable from an efficiency standpoint.

The operating principles developed above in terms of a simplified circuit have been applied to a number of practical circuit forms which are described in the sections following.

Load Circuit

In radar applications the useful load is a magnetron which takes the place of the linear resistance previously considered. Since the magnetron viewed at its input terminals acts essentially like a negatively biased rectifier, additional means must provide for the flow of condenser charging current in a

direction opposite to that of the discharge pulse. This takes the form of a suitably poled diode shunted around the magnetron input terminals. After the main discharge pulse is completed, reactive elements are left with some little energy which tends to redistribute throughout the network. In course of redistribution, additional pulses of lower energy may occur shortly after the main pulse is completed. This tendency is a harmful one if the after-pulses are large, since echoes from short-range targets are obscured. Suppression of after-pulses is assisted by shunting around the diode-magnetron a linear inductance known as a clipping choke. This added inductance slows down the rate at which energy is redistributed, and permits the diode to fulfill its second function of dissipating the greater part of the residual energy. The shunting inductor, too, is made to fill a second function. Through provision of a bifilar winding, it passes heating current to the filament of the magnetron, thereby eliminating the need for high-voltage insulation otherwise required in the filament transformer.

Magnetic Bias

Several arrangements have been worked out for supplying various amounts of bias, some of them using a separate source, others being self-biased.[3] In general the use of external bias leads to a lower demand on the driving tetrode and is associated with pulse production at best efficiency. Circuits dispensing with an external bias source are that much more convenient in use, where the added tube demand and the lower efficiency corresponding can be handled without undue increase of the tube complement. In general the energy delivered to the magnetron is roughly 25 to 55 per cent of the plate energy input, with the higher figure applying to the higher outputs and external bias.

Transformer Coupling

In some cases it is convenient to equip the non-linear coil with primary and secondary windings providing voltage transformation or isolation to avoid adding a transformer for that purpose. The first case arises in the higher-powered pulsers, where the load condenser has to be charged to a voltage greater than the driving tetrode can withstand. For the Western Electric 5D21 tubes customarily used, voltage breakdown occurs near 20 kv, while condenser voltages in certain of the pulsers reach 30 and 40 kv. This situation calls for a step-up ratio from primary to secondary to fit the required potentials. The need for isolation may be illustrated by reference to Fig. 3a where the bias battery E_0 is shown maintained at the plate supply potential above ground. To avoid the resulting insulation problems in a

[3] One widely used circuit using a small amount of self-bias was developed by L. G. Kersta and E. E. Crump.

rectifier built to supply bias, a secondary winding is readily provided on the non-linear coil for connection to the linear coil and to the bias rectifier, which can then be maintained with one side at ground potential.

In either case whenever coupled windings are employed, the inside winding is invariably made to carry the discharge pulse. This provision results in minimum saturation inductance, since the inner winding is brought as close to the magnetic core as the voltage breakdown strength of the intervening dielectric permits. This winding is disposed as uniformly as possible around the core to avoid leakage which would add to the saturation inductance, and so limit the rate of current build-up in the pulse. The other winding can then be disposed with generous spacings, and with partial core coverage if desired.

Pulse Shaping

The oscillation frequency of the magnetron is determined primarily by its internal structure, although it is to some extent a function of the impressed potential. Departure of the driving wave from perfectly rectangular form permits the oscillation frequency to vary during the pulse, to an extent depending upon the size and duration of the departure and upon the characteristics of the magnetron.[4] Frequency modulation thus produced disperses energy over the spectrum. With the receiver band width limited to reduce noise and interference, one effect of this spreading of energy over the spectrum is to cut down the strength of the observed echo. For this reason, other things being equal, rectangularity must be approximated well enough to make the wasted energy a small fraction of that usefully employed.

It is convenient to regard the rectangular wave as synthesized by a series of harmonically related sine waves of appropriate magnitudes. The fundamental component according to this concept has a half period equal to the duration of the pulse, and the other components, progressively smaller in amplitude, have frequencies which are odd harmonics of the fundamental. In the low-power pulser with its rounded discharge wave the harmonic waves are quite small in amplitude. To approach the flat-topped discharge wave necessary in the power pulsers, harmonic components must be built up. This can be done by providing additional resonances in the discharge circuit at the wanted harmonic frequencies.

With the close spacing between circuit elements and their proximity to the pulser box walls, parasitic capacitances of appreciable magnitude add to those normally present. These involve dielectrics of low loss and, since the circuit elements and connecting wires are firmly fixed in position, they are fairly well reproduced. They can be used, therefore, in conjunction

[4] The Magnetron as a Generator of Centimeter Waves, by Fisk, Hagstrum, and Hartman, *B.S.T.J.*, April, 1946.

with added reactors of small size to provide harmonic resonances needed to shape the discharge pulse. These help to bring up the third and fifth, and in some cases higher harmonics.

Results after shaping are shown in Fig. 4 for two extremes of pulse width. The shorter pulse, roughly a quarter microsecond in average duration,

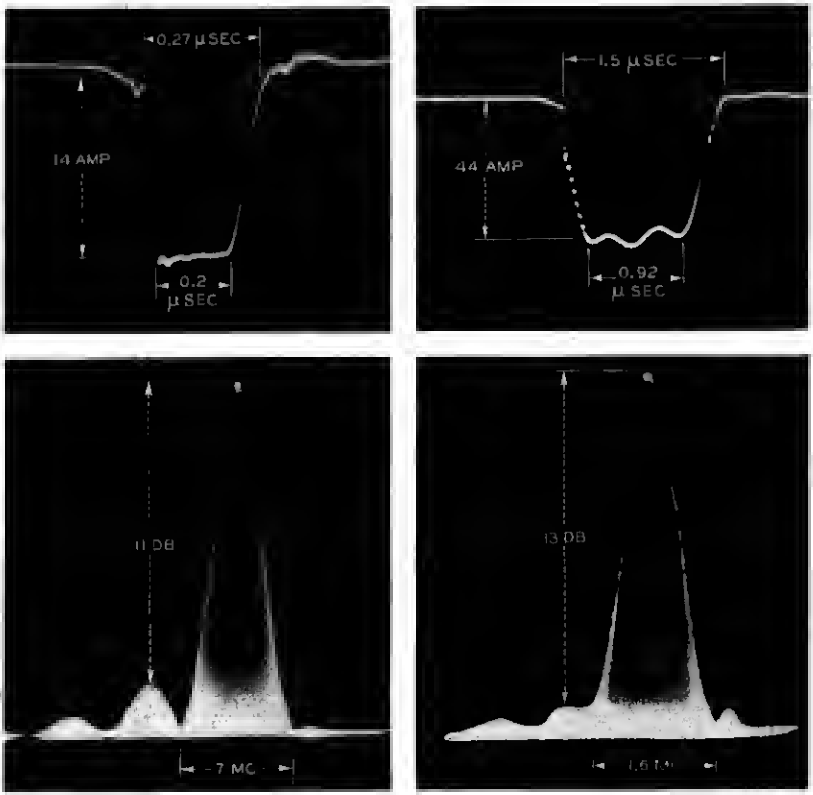

Fig. 4—Shaped magnetron current pulses, together with the radio frequency spectrograms corresponding. Pulse at upper left indicates presence of higb barmonics; pulse at upper right shows strong fifth harmonic and little at higher harmonics. The band width of the main energy lobe, and the dispersion of energy outside tbat band in both cases indicate ncgligibly small effect attributable to frequency modulation.

evidences the presence of fairly high harmonics. The wider pulse, roughly one and a quarter microseconds in average duration, has a strong fifth harmonic and some even harmonics as well.[5] Below each pulse is shown a spectrogram of the corresponding magnetron high-frequency output, which

[5] Magnetron currents are sbown rather than voltages, since current is a far more sensitive indicator of performance.

represents energy as a function of frequency. Different magnetrons are used with the two pulses; their operating frequencies and power capacities differ widely. Apparently frequency modulation exists in both cases to a small extent indicated by the departure of eacb spectrogram from symmetry about a vertical axis. Detailed study, however, shows that the band

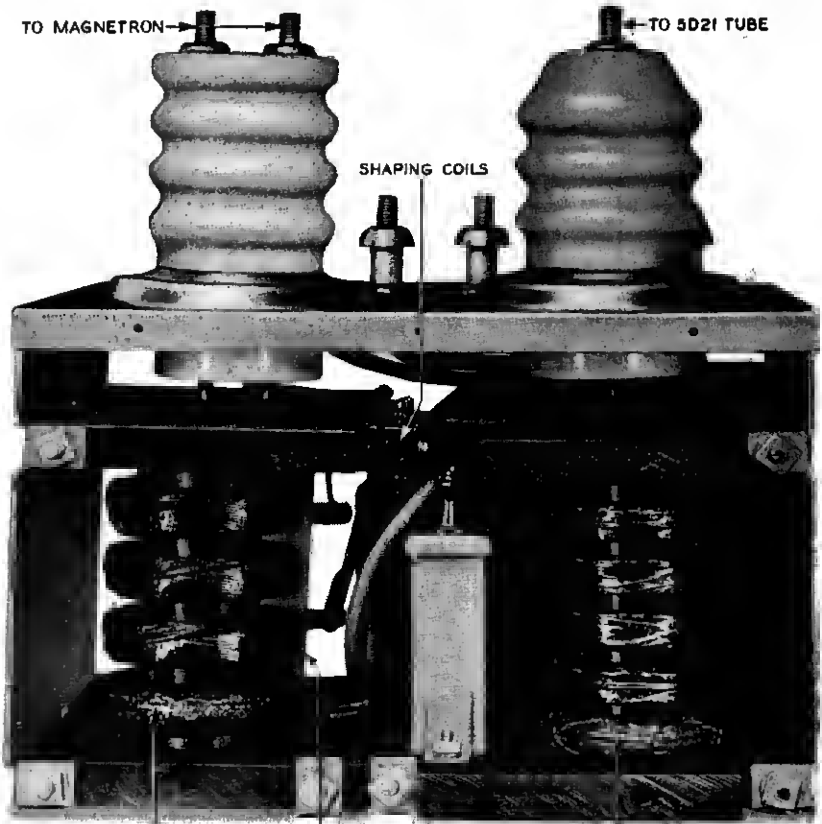

Fig. 5—Typical power pulser network.

width of the main energy lobe differs inappreciably from that with zero frequency modulation, and tbat the dispersion of energy attributable to frequency modulation is negligihly small. The pulses shown therefore provide satisfactory performance witb tbeir respective magnetrons.

Pulser Box

The form in whicb the typical power pulser network appears is shown in Fig. 5. Power peaks generated by tbe particular network sbown are of the

order of 150 kw, with pulse durations of the order of a half microsecond. The non-linear coil here is similar to the one kilogram model pictured in Fig. 1; it is mounted on a panel back of the linear inductor indicated on the Figure. The two larger insulators are used to support high-voltage terminals, the double terminal at the left connecting to the cathode and heater of the magnetron and the single terminal at the right connecting to the tetrode plate. The smaller terminals provide lower-voltage connections including those to the plate power supply of 1000–1500 volts, the bias source where required, and the heating power supply for the magnetron. In use the network is sealed into a closely fitting oil-filled container.

Acknowledgment

The development of coil pulsers was a cooperative enterprise involving a number of different groups in the Laboratories. Design and engineering of the research models were the work of J. M. Manley, P. A. Reiling, L. R. Wrathall, W. R. Bennett, L. W. Hussey and E. M. Roschke. Magnetic cores were developed under the direction of R. M. Bozorth and E. E. Schumacher. Production models were engineered under the direction of F. J. Given. The achievement of successful coil pulsers, moreover, owes much to the efforts of W. H. Doherty and his radar development group.